Asteroid Redirect Robotic Mission (ARRM): Observation Campaign Study

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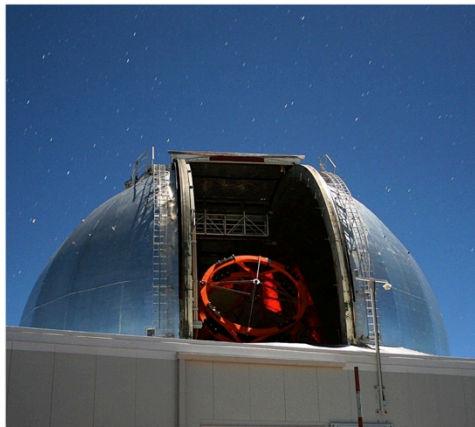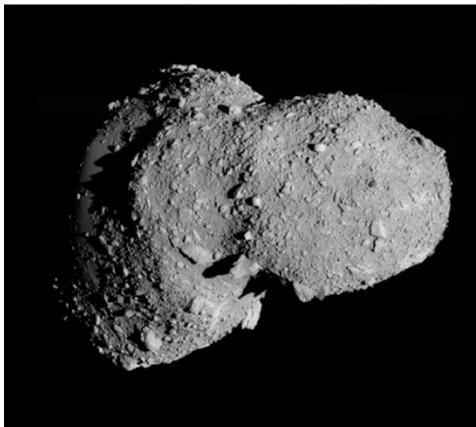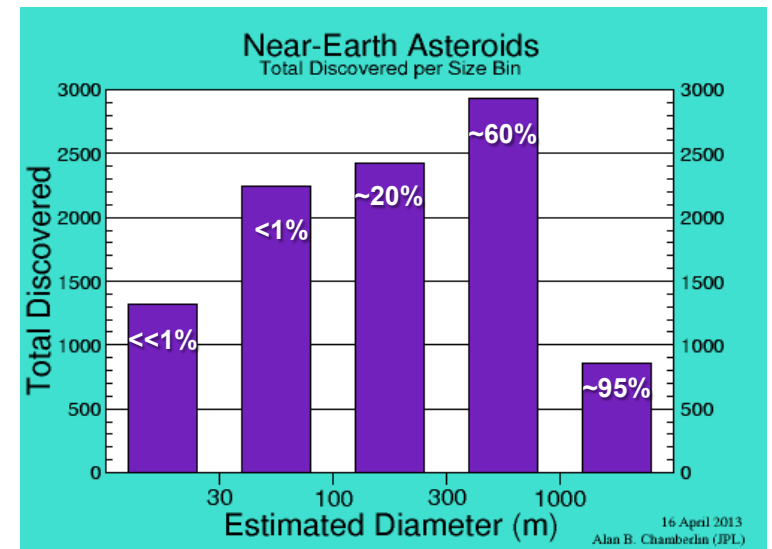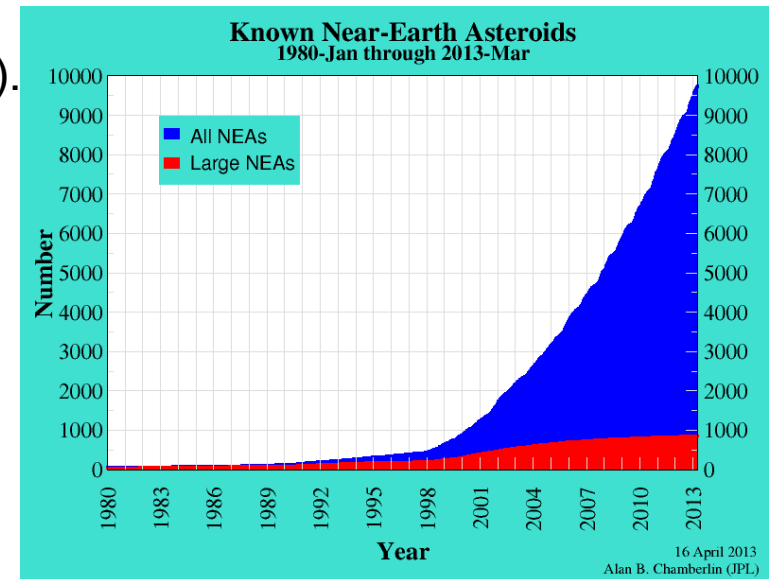
Executive Summary

- Current population models suggest that there are a large number of good ARRM candidate targets, but current surveys are finding only 2 to 3 per year, and only 4 of the known candidates can be adequately characterized (2009 BD, 2011 MD, 2013 EC20, 2008 HU4).

- Discovery of good candidates is challenging, but the rate can be increased to at least 5 per year via near-term enhancements to current survey assets, as well as additional assets that can be online by 2015.

- Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.

- The discovery process alone is not sufficient to identify good candidates: physical characterization is also needed, particularly *re* size and mass.

- Radar is a key characterization asset for ARRM candidates.

- Rapid response is critical for physical characterization of newly discovered ARRM candidates. The process has been successfully exercised for a small candidate asteroid.

Numbers of Near-Earth Asteroids (NEAs)

- 99% of Near-Earth Objects are asteroids (NEAs).

- Current number of known NEAs: ~10,000, discovered at a rate of ~1000 per year.

- Since 1998, NASA's NEO Observation Program has led the international NEO discovery and characterization effort; this responsibility should continue in the search for smaller asteroids.

- 95% of 1-km and larger NEAs have been found; the completion percentage drops for smaller asteroids because the population increases exponentially as size decreases.

- Numbers for 10-m-class NEAs:
  - Estimated population: ~100,000,000
  - Number currently known: ~380
  - Estimated number that meet
    ARRM orbital criteria: ~15,000
  - Number currently known: 14
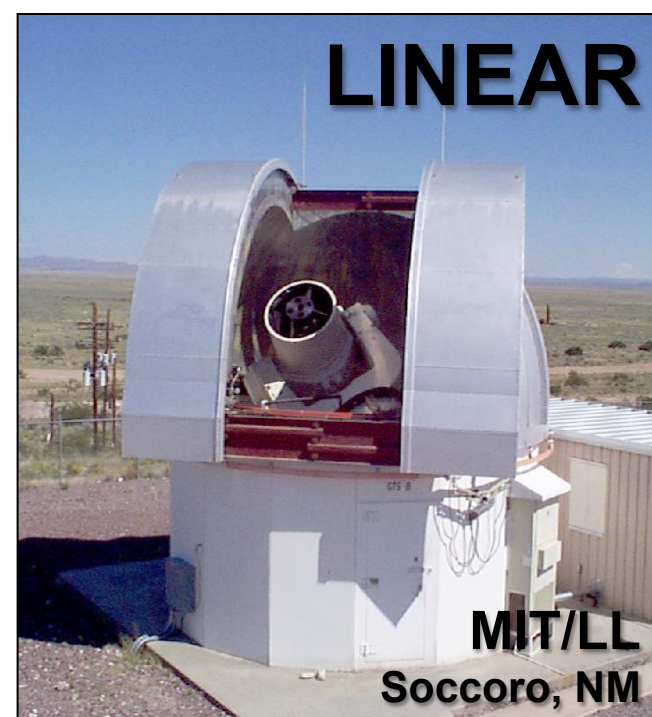

Known Near-Earth Asteroids
1980-Jan through 2013-Mar

All NEAs
Large NEAs

16 April 2013
Alan B. Chamberlin (JPL)

Near-Earth Asteroids
Total Discovered per Size Bin

~60%
~20%
<1%
<<1%
~95%

16 April 2013
Alan B. Chamberlin (JPL)

- US component to International Spaceguard Survey effort has provided 98% of new detections of NEOs since 1998.

- Began with NASA commitment to House Committee on Science in May, 1998 to find at least 90% of 1 km NEOs.
  – Averaged ~$4M/year Research funding 2002-2010

- NASA Authorization Act of 2005 provided additional direction:
  "…plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue within 15 years [by 2020].

- Current Program Objective: Discover $\geq$ 90% of NEOs larger than 140 meters in size as soon as possible.
  – Starting with FY2012, has $20.5M/year

NASA's NEO Search Programs: Current Systems

Catalina Sky Survey — U of AZ, Arizona & Australia

Pan-STARRS — U of HI, Haleakala, Maui
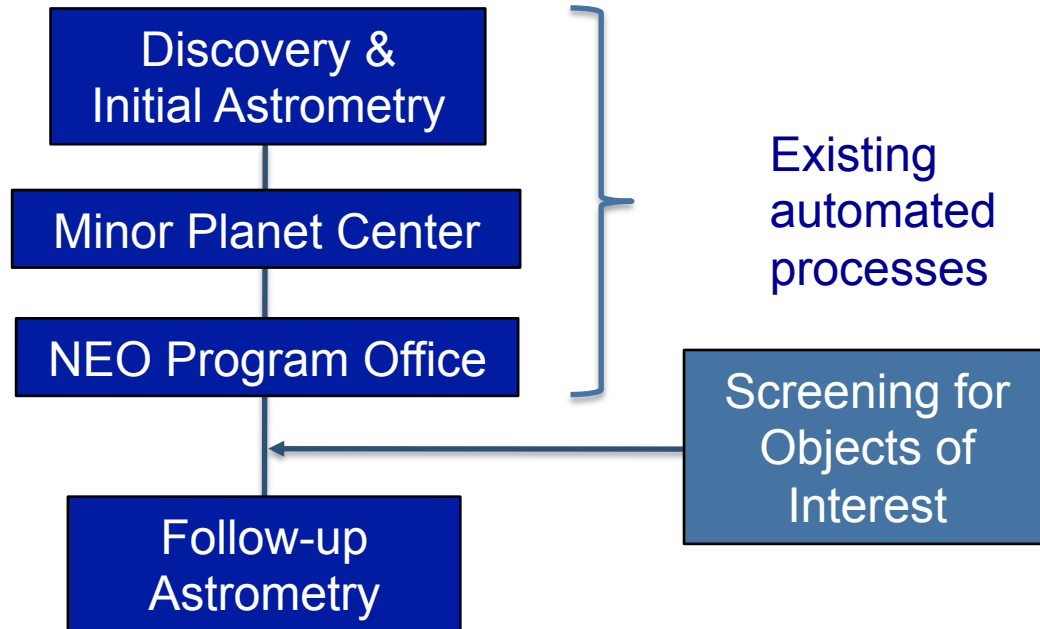
LINEAR — MIT/LL, Soccoro, NM

- Currently, most Near-Earth Asteroid discoveries are made by:
  Catalina Sky Survey (60%), Pan-STARRS-1 (30%), and LINEAR (3%).

- Enhancements and new surveys can come online in the next 2 years. Some will require additional funding.

- These enhancements will increase capabilities to find hazardous asteroids as well as ARRM candidate targets.

Discovery & Characterization Processes

**Discovery,
Orbit Determination,
Rough Size
Estimation**

Discovery &
Initial Astrometry

Minor Planet Center

NEO Program Office

Existing
automated
processes

Screening for
Objects of
Interest

**Physical
Characterization**

Follow-up
Astrometry

Astrometry,
Photometry,
Light Curves,
Colors

Orbit, area/mass
ratio, size, rot. rate,
spectral type

Visible & IR
Spectroscopy,
IR radiometry

Spectral type, size,
& mass, possibly
composition

Radar

Precise Orbit,
size & rotation
rate
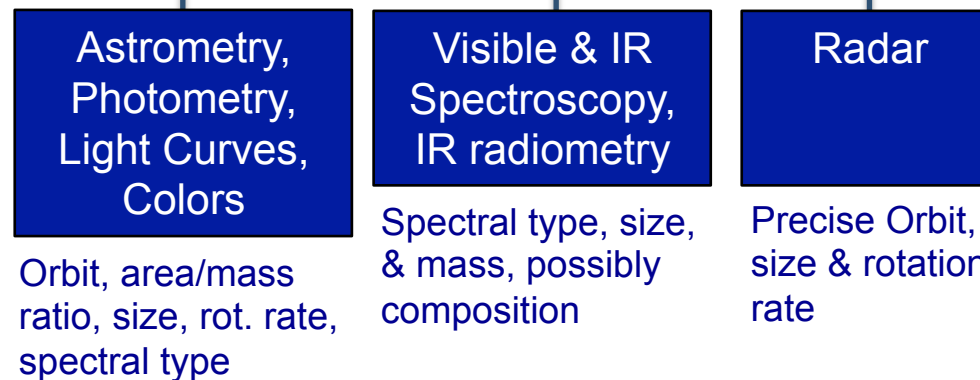
Characteristics of ARRM Target Candidates

$V_{infinity}$ is the velocity of the asteroid relative to the Earth during an encounter, with the acceleration due to the Earth's gravity removed.

	Characteristic	Reference Value
Orbital	Orbit: $V_{infinity}$ relative to Earth	< 2 km/s desired; upper bound ~2.6 km/s
	Orbit: Natural approach to Earth	Orbit-to-orbit distance < ~3 million miles Natural approach to Earth in early 2020s
Physical	Size and Aspect Ratio	Estimated mean size: 7 to 10 m Upper limit on maximum dimension: ~14 m Aspect ratio < 2:1
	Mass	<1,000 metric tons (Upper bound decreases as $V_{infinity}$ increases)
	Spin Rate	< 2 rpm
	Spectral Class	Known Type preferred, but not required (C-type with hydrated minerals desired)

Current List of Potential ARRM Candidates

Name	Apparent Magnitude at First Detection	Estimated Size (m)	V_∞ (km/s)	Earth Approach Date	Distance at Approach (AU)*	Maximum Returnable Mass (t)[†]
Good retrieval trajectories found						
2007 UN12	17.7	3 - 14	1.2	9/15/2020	0.043	490
2008 EA9	21.0	5 - 22	1.9	11/15/2020	0.073	130
2013 EC20	17.7	2 - 4	2.6	3/15/2021	0.067	120
2010 UE51	19.2	4 - 17	1.2	10/15/2022	0.023	130
2009 BD	18.4	4 - 8	0.7	6/26/2023	0.199	590
2011 MD	19.2	5 - 18	0.9	8/10/2024	0.150	690
2008 HU4	17.9	4 - 18	0.5	3/27/2026	0.149	1600
Good retrieval trajectories may be possible						
2010 XU10	20.0	6 - 25	2.5	10/22/2021	0.167	TBD
2012 WR10	19.0	4 - 15	2.6	12/6/2021	0.292	TBD
2011 BQ50	22.8	4 - 17	2.6	11/4/2022	0.078	TBD
2011 PN1	22.0	6 - 24	n/a	6/30/2023	0.300	TBD
2005 QP87	18.2	5 - 22	1.5	3/1/2024	0.457	TBD
2010 AN61	19.4	7 - 30	2.6	6/10/2025	0.251	TBD
2013 GH66	20.3	5 - 18	2.0	4/15/2025	0.894	TBD

Current baseline → 2009 BD

KISS baseline → 2008 HU4

*1 AU = 93,000,000 miles;   [†]Assumes Falcon Heavy launch vehicle and launch dates no earlier than 2017.

- 14 known asteroids meet the rough size and orbit criteria for ARRM.

- But, most were not physically characterized after discovery due to small size.

- These potential candidates are being discovered at a rate of **2-3 per year**.

- Enhancements to capabilities can increase this discovery rate.

- 4 candidates on this list can be at least partially characterized:
  2009 BD,   2011 MD,   2013 EC20   and   2008 HU4.

Primary Enhancements for ARRM Candidate Discovery

- **NEO Time on DARPA Space Surveillance Telescope**
  - Large 3.6m telescope, first light: Feb 2011, now in testing.
  - Eventual operations by AFSPC for DoD Space Situational Awareness.
  - Testing of NEO detection capability: Sep 2013.

- **Enhancing Pan-STARRS 1, Completing Pan-STARRS 2**
  - Increase NEO search time to 100% on PS1: Early 2014.
  - Complete PS2 (improved copy of PS1): Late 2014.
  - Simulations suggest the ARRM candidate discovery rate for PS2 alone at 100% will be ~5 per year.

- **Accelerated Completion of ATLAS**
  - Set of small telescopes with extremely wide fields of view covering the entire night sky every night, but not as deeply.
  - Final design selection soon. Completion: Early 2015.
  - Simulations suggest the ARRM candidate discovery rate for ATLAS will be ~10 per year.
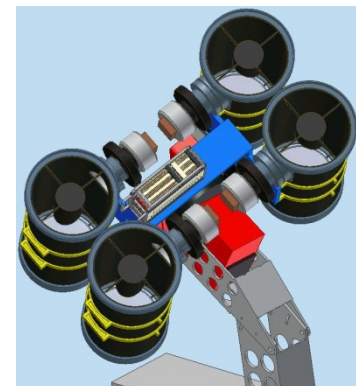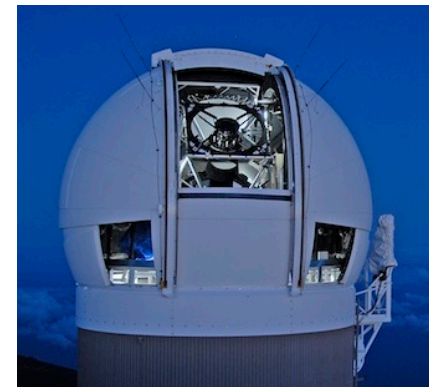
Options for Increasing the ARRM Candidate Discovery Rate

	Facility	V_{lim}	FOV (deg²)	In Work or Potential Improvements	Ops Date	Notional ARRM discoveries per year*
Current Surveys	Catalina Sky Survey:			Increase ML field of view 4x	Late 2013	2-3
	Mt. Bigelow	19.5	8	Increase MB FOV 2.5x	Late 2014	1-2
	Mt. Lemmon	21.5	1.2	Retune observation cadence	Mid 2014	3-5
	Pan-STARRS 1	21.5	7	Increase NEO time to 50%	Late 2013	2-4
				Increase NEO time to 100%	Early 2014	4-8
Future Surveys	DARPA SST	22+	6	Schedule some NEO time	Sep. 2013	2-5
	Palomar Transient Facility (PTF)	21	7	Improve software to detect streaked objects	Late 2013	1-2
	Pan-STARRS 2	22	7	Request 100% NEO time	Late 2014	5-10
	ATLAS (North)	20	40	Entire night sky every night x2	Early 2015	8-16

*Discoveries per year that meet ARRM's rough size and orbit criteria for retrieval. V_{lim} = limiting magnitude
N.B. Predictions for future discovery rates are based on extrapolated coverage and cadence.

Discovery rates are not additive. There will be duplications of detections, particularly in the optimistic scenarios.

Summary on Future Discovery Rate of ARRM Candidates

- The ARRM candidate discovery rate will almost certainly **increase** due to enhancements to existing surveys and new surveys coming online.

- Several asteroid survey enhancements are already in process and funded by the NEOO Program. Some could be accelerated with additional funding.

- A conservative projection, based on study of enhancements, is that the discovery rate will increase to **at least 5 per year**.

- Search for ARRM candidates will continue until final selection.

- With at least another 3-4 years to accumulate discoveries, at least **15 more candidates are expected**.

- With rapid post-discovery characterization capabilities in place, there will be better opportunities to physically characterize future ARRM discoveries.

- Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.

Physical Characterization of ARRM Candidates

- **Radar** is essential for obtaining an accurate estimate of size and shape to within ~2 m, as well as rotation state.

- Ground-based and space-based **IR** measurements are important for estimating albedo and spectral class, and from these an approximate density can be inferred.

- **Light curves** are important to estimate shape and rotation state.

- **Long-arc high-precision astrometry** is important for determining the area-to-mass ratio.

- Mass is estimated from size and shape using an inferred or assumed density, and it should be constrained by the estimate of the area-to-mass ratio. Even so, mass may only be known to within a factor of 3 or 4.

- Final ARRM target selection may depend largely on how the estimated upper bound on the mass of each candidate compares with the return mass capability for that candidate.
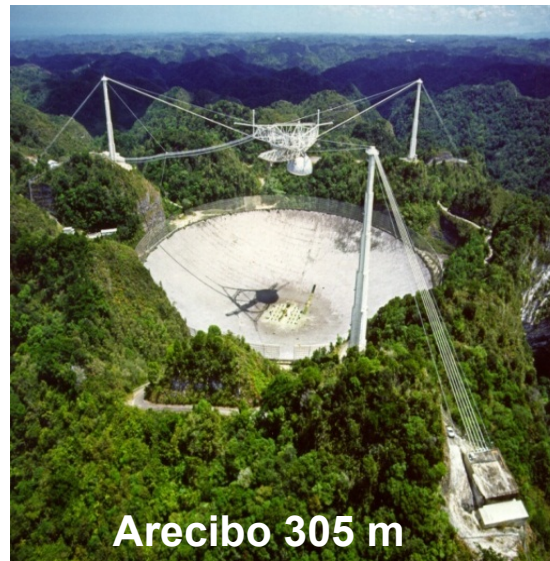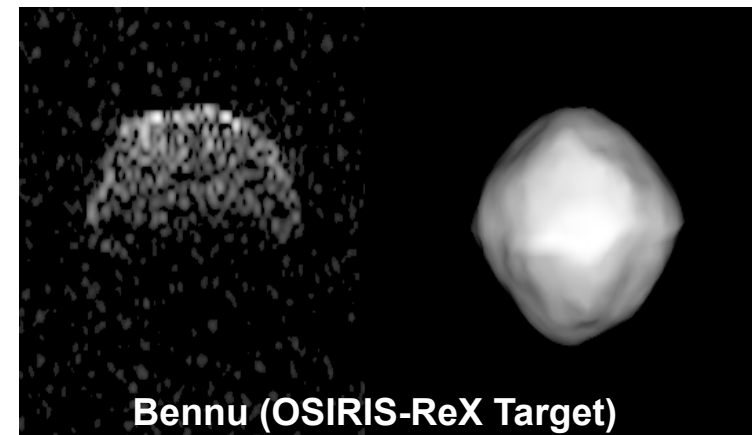
Assumed albedo
ρ = 0.04

Assumed albedo
ρ = 0.34

Radar Observations of NEOs

Goldstone 70 m

Arecibo 305 m

Bennu (OSIRIS-ReX Target)

2012 XB112, size ~ 2 m

← Range

Doppler frequency →

1E+09 1.5E+09 2E+09 2.5E+09

- These are complementary capabilities.
- Currently, 70-80 NEOs are observed every year.
- A 10-m-class ARRM candidate must pass within ~5 lunar distances to be detected; ~80% of the 14 known candidates could have been detected.
- Radar observations can provide:
  - Size and shape to within ~2 meters.
  - High precision range/Doppler orbit data.
  - Spin rate, surface density and roughness.
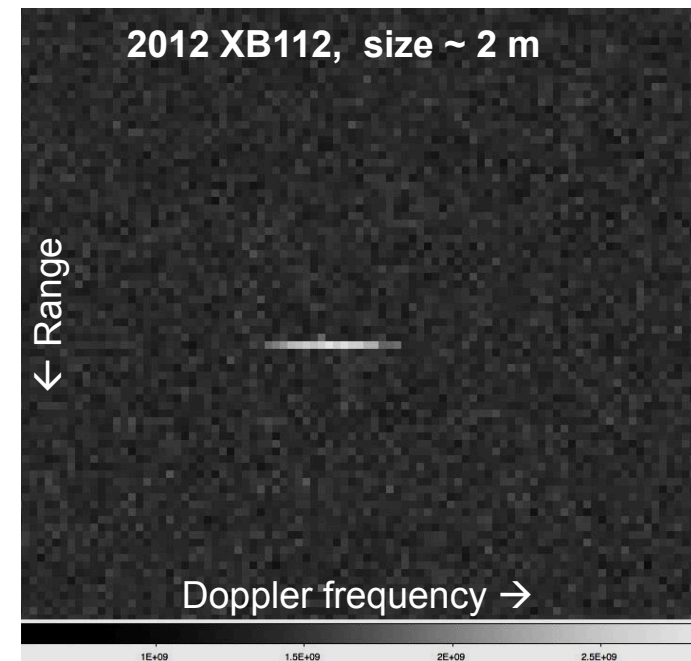
Infrared Characterization of NEOs
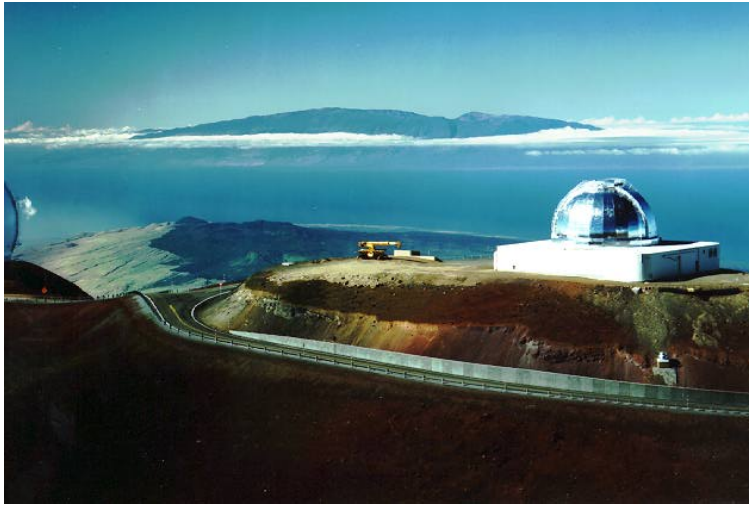
NASA InfraRed Telescope Facility (IRTF)

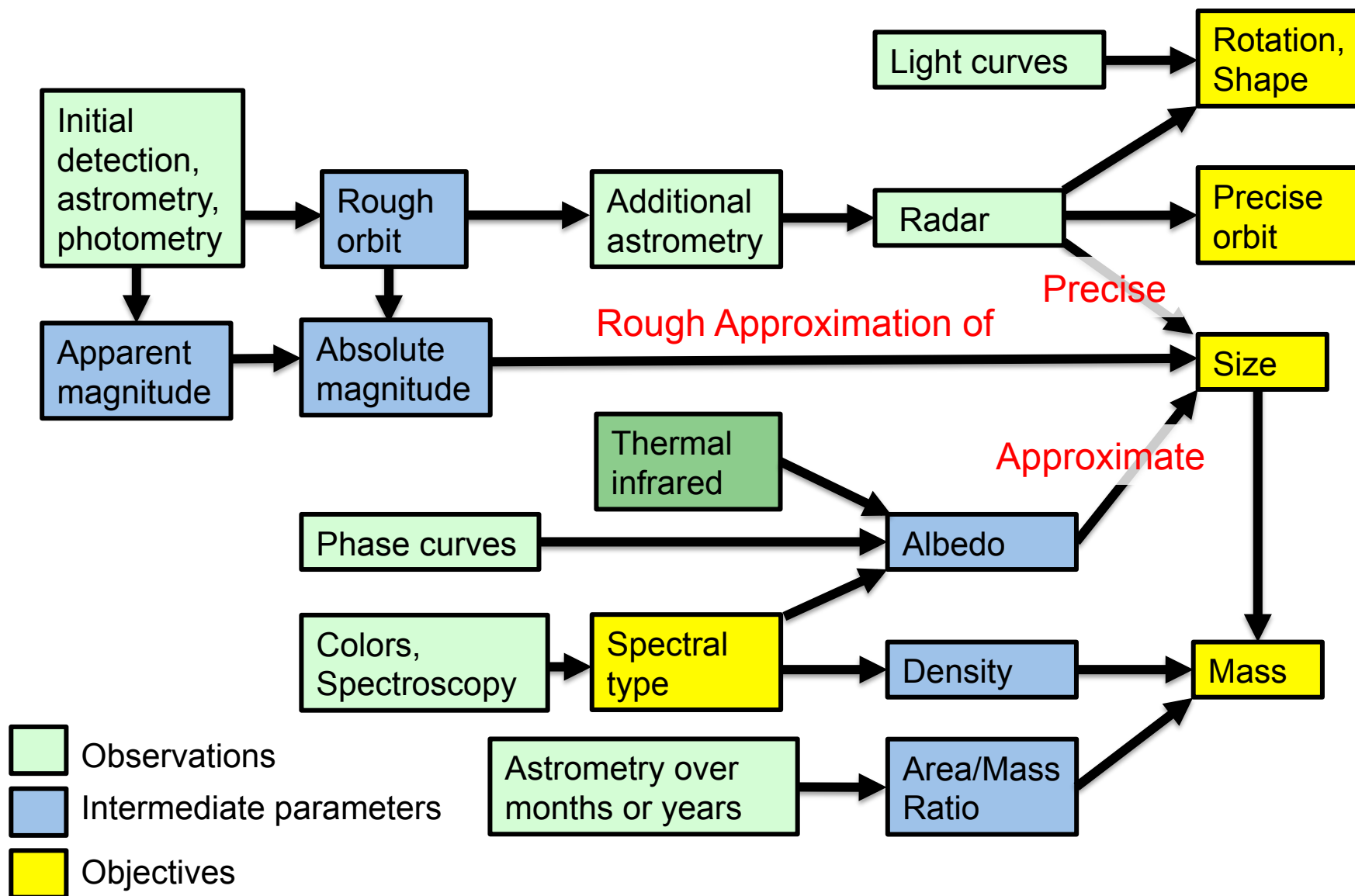- Dedicated Planetary Science Observatory
- Characterization of Comets and Asteroids
- Spectroscopy and Thermal Signatures
- On-call for Rapid Response on Discoveries

Spitzer Infrared Space Telescope

- Orbit about Sun, ~176 million km from Earth
- In extended Warm-phase mission
- Characterization of Comets and Asteroids
- Thermal Signatures, Albedo/Sizes of NEOs
- Longer time needed for scheduling

NEA Characterization Process

Light curves → **Rotation, Shape**

Initial detection, astrometry, photometry → **Rough orbit** → **Additional astrometry** → **Radar**

Radar → **Rotation, Shape**

Radar → **Precise orbit**

Radar → Precise → **Size**

Initial detection, astrometry, photometry → **Apparent magnitude**

Rough orbit → **Absolute magnitude**

Apparent magnitude → **Absolute magnitude** → Rough Approximation of → **Size**

Thermal infrared → **Albedo**

Phase curves → **Albedo**

Albedo → Approximate → **Size**

Colors, Spectroscopy → **Spectral type** → **Albedo**

Spectral type → **Density** → **Mass**

Size → **Mass**

Astrometry over months or years → **Area/Mass Ratio** → **Mass**

Legend:
- 🟩 Observations
- 🟦 Intermediate parameters
- 🟨 Objectives

Asteroid Redirect Mission • Mission Formulation Review • For Public Release   15

ARM Candidate Characterization Process Exercised for 2013 EC20

- Discovered 7 March 2013 (during ARM study), by Catalina Sky Survey.
  - Initial size estimate: ~6m, Close approach 8 March at 0.5 lunar distance.
- Manually recognized as potential ARRM target (process now automated).
- Request follow-up astrometry ⟹ orbit update to enable IRTF observation.
- IRTF Interrupt: Spectra and thermal IR [Moskovitz & Binzel]:
  - L- or Xe-type, inferred albedo range of 0.1-0.4, density range of 2.0-3.0 g/cc
  - Diameter = 2.6 - 8.4 m, mass = 20 - 930 t
  - Spin rate ~0.5 rpm
- Arecibo radar @~3 lunar dist. [Borozovic]:
  - Diameter = 1.5 - 3 m ⟹ albedo > ~0.4
  - Constrains mass to < 50 t
  - Spin rate: 0.5 – 2 rpm
- Preliminary mission design indicates a feasible retrieval trajectory for 2021.
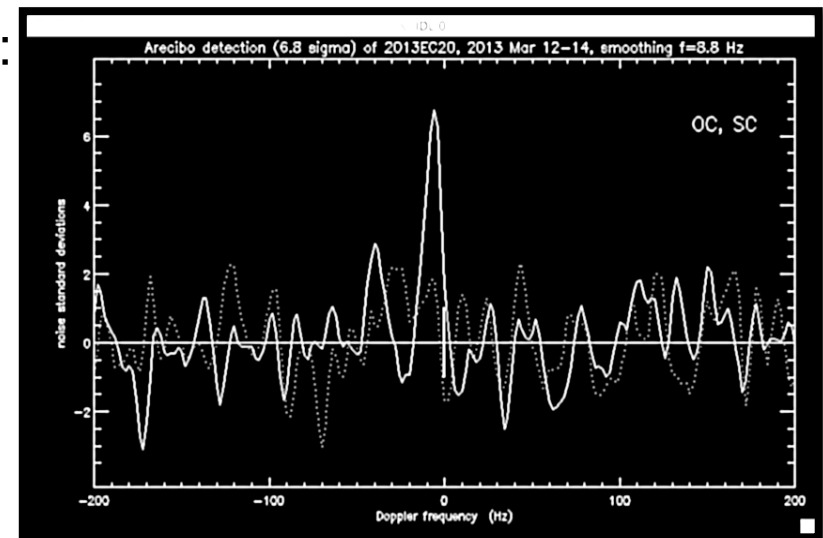
ARM Candidate Characterization Process

- **Rapid response** after discovery is essential while the asteroid is within range of characterization assets, since the asteroid will not likely be any closer for many years.

- Need rapid response for **radar** observation at Goldstone and/or Arecibo. The Goldstone interrupt response process especially needs to be streamlined.

- **Follow-up astrometry** from the observing community is essential for characterization.

- Request interrupt observations from **IRTF** and other large-aperture assets that can provide thermal IR data for faint objects. (This may require additional interagency agreements for target-of-opportunity observing time.)

- Obtain high precision astrometry, photometry and light curve measurements from geographically dispersed observatories (e.g. Palomar, Keck, European Southern Observatory in Chile).

- Solicit support from smaller telescopes, including amateurs, to provide quick follow-up astrometry and photometry.

Currently Known Characteristics of Current Candidates

| Characteristic	Reference Value	2009 BD	2011 MD	2013 EC20	2008 HU4	2007 UN12	2010 UE51
Orbit Confidence	OCC < 4	Excellent	Good	Recoverable	Recoverable	Recoverable	Good
Orbit: Vinfinity (km/s)	< 2 (< 2.6 req.)	0.7	0.9	2.6	0.5	1.2	1.2
Orbit: Natural return year	Early 2020s (2020-26)	2023	2024	2020	2026	2020	2023
Size (m)	< 10 m and > 7 m	4-8 [1]	< 30 [4]	2-3 [6]	< 28 [4]	< 22 [4]	< 27 [4]
Mass (t)	< 1000 t	< 350 [2]	< 50,000 [5]	< 50	< 40,000 [5]	< 20,000 [5]	< 36,000 [5]
Spin Rate (rpm)	< 2	< 0.01 [3]	0.1 [3]	< 2 [6]	Unknown	Unknown	Unknown
Spectral Class	Known (C preferred)	Unknown	Unknown	L or Xe	Unknown	Unknown	Unknown
Next Observation Opportunity	A=Astrometric O=Optical IR=Infrared R=Radar	2013-Oct: IR	2014: IR?	2013-Aug: A?	2016-Apr: A, O?, R	None	2014: IR??

Notes: [1] Upper bound from NEOWISE stacked non-detection, lower bound assumes upper bound albedo of 50%; [2] Lower bound Area/Mass Ratio: 1.55×10^{-4} m^2/kg from Farnocchia et al.; [3] Magdalena Ridge lightcurve; [4] Lower bound on abs. mag. and lower bound albedo of 3%; [5] Upper bound density of 3.5 g/cc; [6] Arecibo radar.

NEO Characterization Enhancements

Radar (Goldstone and Arecibo)
- Increase time for NEO observations.
- Streamline Rapid Response capabilities.

Goldstone Radar

Arecibo Observatory
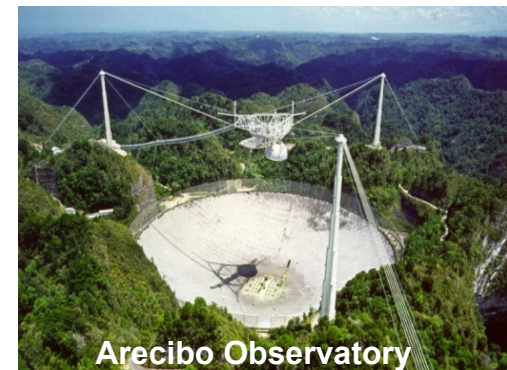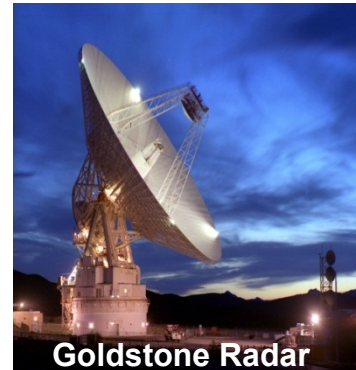
NASA InfraRed Telescope Facility (IRTF)
- Increase On-call for Rapid Response.
- Improve Instrumentation for Spectroscopy and Thermal Signatures.

Reactivate NEOWISE
- ~3 year warm phase dedicated to NEO Search/Characterization data collection.

NEOWISE

JPL
Sun-synch LEO

Summary

- Simulations suggest there are thousands of suitable ARRM candidate targets; the challenge is to find them.

- Candidates are currently being discovered at the rate of 2-3 per year.

- With several survey enhancements in process, and new surveys coming online within the next 2 years, the ARRM candidate discovery rate should increase to at least 5 per year.

- Discovery enhancements will add capability to find hazardous asteroids as well as ARRM candidate targets.

- Rapid response after discovery is critical for physical characterization of ARRM candidates. The process has already been successfully exercised for a difficult-to-characterize candidate.

- Goldstone and Arecibo radars are key characterization assets for ARRM candidates because they provide accurate estimates of size and rotation state.

- Other major assets for characterization are available. Interagency agreements for target-of-opportunity observing time from important non-NASA facilities (eg. Subaru) can be negotiated.